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First observation of the Venus UV dayglow at limb from SPICAV/VEX

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[1] We present the first limb observations of the dayglow emissions by the UV channel of SPICAV aboard Venus Express between October and December 2011. The CO Cameron bands between 180–260 nm and CO_2^+ doublet at 289 nm are clearly identified for the first time in the Venusian dayglow. The Cameron bands brightness peaks at 137.5 ± 1.5 km with a peak brightness of 2000 ± 100 kR and the CO_2^+ doublet peaks at 135.5 ± 2.5 km with a peak brightness of 270 ± 20 kR. The temperature near 145 km derived from the CO_2^+ bands scale height is 290 ± 60 K, in good agreement with other types of measurement. The spectral shape of the Cameron bands is similar to the spectral shape of the Cameron bands observed on Mars with the same coarse 10 nm resolution. The stronger brightness of the Venusian dayglow with respect to Mars dayglow in the 200–300 nm range cannot be explained only by the distance to the Sun and by the difference in EUV solar flux at the time of the observations. **Citation:** Chaufray, J.-Y., J.-L. Bertaux, and F. Leblanc (2012), First observation of the Venus UV dayglow at limb from SPICAV/VEX, *Geophys. Res. Lett.*, *39*, L20201, doi:10.1029/2012GL053626.

1. Introduction

[2] The first UV emission observed on Venus was the strong HI (121.6 nm) Lyman-α emission by the Mariner 5 and Venera 4 ultraviolet photometers [*Barth et al.*, 1967; *Kurt et al.*, 1968]. This emission has been studied intensively from later observations [e.g., *Chaufray et al.*, 2012, and references therein]. Several other emissions were observed during the Mariner 10 and Venera 11 and 12 flybys associated to HeII (30.4 nm), HeI (58.4 nm), OII (83.4 nm), OI (130.4 nm), CO ($A^1\Pi - X^1\Sigma^+$ near 150 nm) and CI (165.7 nm) [*Broadfoot et al.*, 1974; *Bertaux et al.*, 1981]. The OUVS instrument on Pioneer Venus Orbiter detected a few new emissions : OI (135.6 nm), CI (156.1 nm) and OI (297.2 nm) [*Stewart et al.*, 1979]. The analysis of these observations has been reviewed by *Fox and Bougher* [1991]. More recently, mid-resolution UV spectra on the Venusian disk have been reported using the Hopkins Ultraviolet Telescope (HUT) covering the spectral range of 82–184 nm [*Feldman et al.*, 2000] at 0.4 nm resolution and Cassini UVIS spectrometer during the Venus flyby in June 1999 covering the EUV (56.3–118.2 nm) and FUV (111.5–191.2 nm) spectral range at 0.37 nm resolution [*Gérard et al.*, 2011; *Hubert et al.*, 2010, 2012]. Several new lines were identified associated to HI (97.3 nm, 102.6 nm), OI (98.9 nm, 104 nm), NI (91.9 nm, 109.7, 113.4, 119.2, 120.0 nm), CI(111.4 nm, 115.8 nm, 126.1 nm, 127.7 nm), CII (133.5 nm) and CO (108.8, 115.2, 159.7 nm and possibly 107.6 nm). The CO Hopfield-Birge bands ($C^1\Sigma^+ - X^1\Sigma^+$) at 108.8 and ($B^1\Sigma^+ - X^1\Sigma^+$) at 115.2 nm were also present in the Galileo EUV spectrum of Venus but not identified due to the 3 nm resolution [*Hord et al.*, 1991; *Feldman et al.*, 2000]. All the emission lines, except H (121.6 nm) and He (58.4 nm) were observed only on the Venusian disk, and therefore no vertical profile could be derived. The comparison between the Venus and Mars UV dayglow spectra [*Feldman et al.*, 2000; *Gérard et al.*, 2011] shows similar features excepting argon emission lines not observed on Venus but observed on Mars. On Mars, strong emissions have been observed at longer wavelengths associated to CO Cameron bands ($a^3\Pi - X^1\Sigma^+$) (180–250 nm) and CO_2^+ ($B^2\Sigma^+ - X^2\Pi$) doublet at 289 nm. These are the strongest emissions observed in the 110–320 nm range at the ionospheric peak [*Leblanc et al.*, 2006; *Simon et al.*, 2009]. Because the Martian and Venusian atmospheres are very similar in composition (CO_2 and N_2) and in their EUV dayglow spectra, there is no doubt that these emissions should also be present in Venus dayglow but they have never been observed. *Stewart et al.* [1979] identified a possible emission line of the Cameron bands at 206.8 nm on the nightside of the Venusian disk, but not the full bands as observed on Mars. In this study, we report the first clear identification of the Cameron and CO_2^+ ($B^2\Sigma^+ - X^2\Pi$) emissions observed at limb on Venus with a 10 nm resolution (Section 2). We also derive the first vertical profiles (Section 3) of the dayglow emission associated to CO_2 dissociation / ionization and compare these results to Martian emissions (Section 4) observed with the similar instrument (SPICAM-UV) on Mars Express.

2. Observations and Data Processing

[3] The SPICAV-UV channel is described in detail in *Bertaux et al.* [2007] and is nearly identical to the UV channel of SPICAM on Mars Express [*Bertaux et al.*, 2006]. For both UV spectrometers, the light flux is collected by an off-axis parabolic mirror. A mechanical slit is placed at the focal plane of the mirror. This slit is divided into two parts: a narrow part gives a spectral resolution of ∼1.5 nm and the wide part gives a coarser resolution ∼10 nm but a higher sensitivity [*Bertaux et al.*, 2007]. The various modes of CCD readout have been described in *Bertaux et al.* [2006]. Two modes have been used for the measurements of the Venusian UV dayglow. The alignment mode is used to obtain a complete image of the CCD by groups of 5 lines with 1

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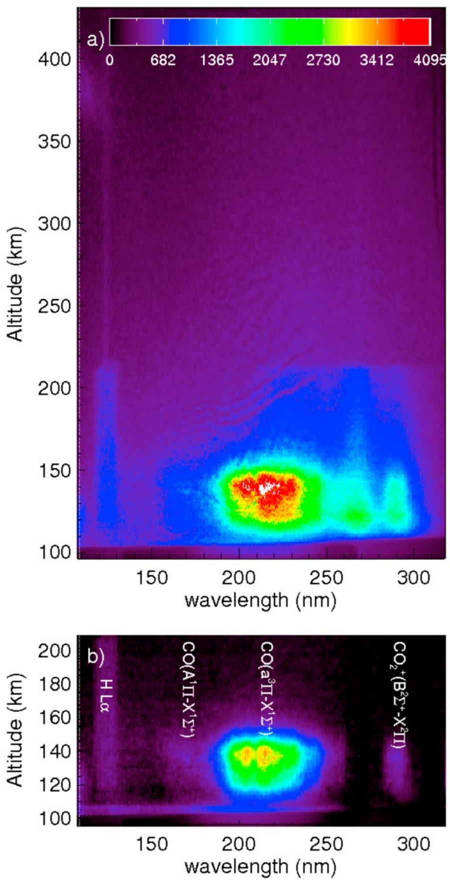

Figure 1. (a) Reconstructed raw image obtained using the alignment mode. Light coming through the wide part of the slit is seen for lines scanning altitudes lower than 220 km while light coming through the narrow part of the slit seen for CCD lines scanning altitude above 220 km. (b) Processed image obtained after offset, dark current and scattered light correction. Only the upper part of the CCD where dayglow emissions are observed is displayed. The emissions observed are the HI Lyman-α line at 121.6 nm, the CO ($A^1\Pi - X^1\Sigma^+$) fourth positive bands between 150–170 nm, and observed for the first time, the CO ($a^3\Pi - X^1\Sigma^+$) Cameron bands between 180–260 nm and CO_2^+ ($B^2\Sigma^+ - X^2\Pi$) at 289 nm. The altitudes correspond to altitudes of the tangent point.

overlap. The binning mode is used with 16 lines grouped together with the first line positioned at the line 200 of the CCD. The solar zenith angles of the tangent point covered by the observations vary between 20–30° for the alignment mode observations and between 20–60° for the binning mode observations. The F10.7 index between October and December 2011 was ~140 and MgII index ~0.07.

[4] An example of a complete raw image obtained with the alignment mode is displayed in Figure 1a.

[5] This raw image is composed of the dayglow emissions, the instrumental bias (offset, dark current) as well as a strong UV background of solar light scattered by the Venusian lower atmosphere and entering the instrument as stray light. The raw image also shows that the upper lines of the CCD (low altitudes) are less sensitive than the rest of the CCD. The instrumental bias are corrected using the standard methods described in *Bertaux et al.* [2006]. We also perform a flatfield correction and subtract the solar scattered light. The corrected image of the upper part of the CCD is displayed in Figure 1b. The spectral features observed in this image are indicated and correspond to CO ($A^1\Pi - X^1\Sigma^+$) bands (fourth positive) near 150 nm, CO($a^3\Pi - X^1\Sigma^+$) bands (Cameron) between 180–260 nm, the CO_2^+ ($B^2\Sigma^+ - X^2\Pi$) doublet at 289 nm and the H Lyman-α line at 121.6 nm. To correct the solar scattered light, we use other observations were the dayglow emissions are mainly in the less sensitive upper part of the CCD and therefore, only the solar scattered light is present on the rest of the CCD. The spectral shape of the solar scattered light is derived from these observations. We then assume that the spectral shape of the solar scattered light is the same from one observation to another. Based on what we observed on Mars [*Leblanc et al.*, 2006], we also assume that the signal observed in all data at wavelength λ = 270 nm and 300 nm only contains scattered light. The reference solar scattered spectra is then linearly fitted to the raw spectra at these two wavelengths for each line of the CCD (Figure 2, left). The signal obtained after subtracting the scattered light is then converted into physical units (kR/nm) as described by *Bertaux et al.* [2006]. An example of spectral profile obtained near 137 km is displayed in Figure 2 (right) and compared to a Martian dayglow observation obtained by SPICAM/MEX with the same coarse resolution as well as the 1.5 nm resolution used by *Leblanc et al.* [2006]. The spectral shape of the CO Cameron bands is very similar on Venus and Mars suggesting that similar production mechanisms are occurring on both planets. The Martian spectra show that the O 297 nm line and the CO_2^+ doublet at 289 nm as well as the HI (121.6 nm) and OI (130.4 nm) lines are not resolved at low resolution.

3. Vertical Profiles

[6] The total brightness of the Cameron bands system and the CO_2^+ doublet is computed using the method described in *Leblanc et al.* [2006].

[7] The vertical profile of the Cameron bands system is displayed on Figure 3a from the two modes of observations described in section 2. The peak altitude of the emission is not observed with the binning mode due to the saturation of the CCD above 500 kR. From the set of alignment mode observations, we derive a peak altitude of the Cameron bands brightness of 137 ± 1.5 km. This altitude is close to the altitude of the ionospheric peak measured by the Venus Express Radio Science (VeRa) experiment [*Pätzold et al.*, 2009]. The Cameron bands brightness measured at limb at this altitude is 2.0 ± 0.1MR corresponding to 25.3 kR when converting to zenith brightness above subsolar point. This is half the value (~47. kR) derived from *Fox* [1992] (when converting to subsolar point using a $\cos^{1/2}$ law and rescaling linearly the values at F10.7 = 70 and F10.7 = 200 to F10.7 = 140) or more recently (~36 kR when converting to subsolar intensity and rescaling from F10.7 = 80 to F10.7 = 140) by the electron transport model TRANS-VENUS described by *Gronoff et al.* [2008]. If the *Erdman and Zipf* [1983] cross section for electron impact dissociative excitation of CO_2 was used the discrepancy would be even worse [*Fox*, 1992]. The vertical profile of the CO_2^+ doublet brightness is displayed on Figure 3b. A small part (~10–15% on Mars) of this emission could be due to the O line at 297 nm. The peak of the emission is observed at 135.5 ± 2.5 km, but is less

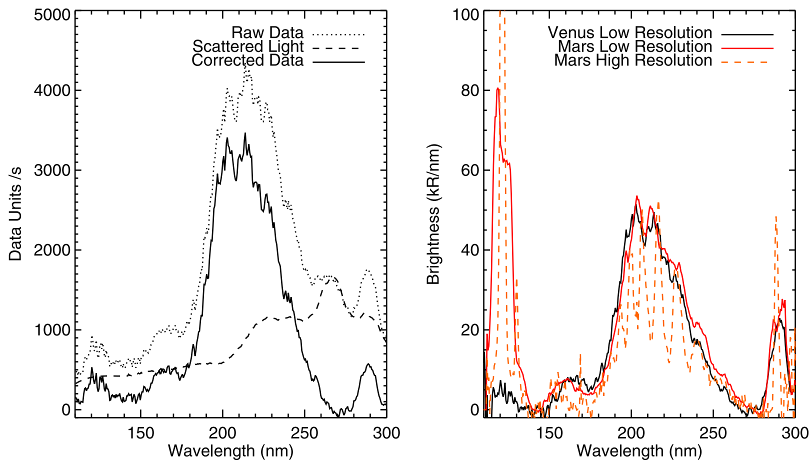

Figure 2. (left) Example of spectra obtained after instrument offset and dark current correction (dotted line) before (dashed line) and after (solid line) scattered light correction. The scattered light profile is also displayed (dotted line). (right) Comparison between the Venusian dayglow profile obtained by SPICAV/VEX (black line) and the Martian dayglow observed by SPICAM/MEX between 160–180 km and multiplied by 120 to scale the Venusian profile at the same 10 nm spectral resolution (solid red line) and with a 1.5 nm spectral resolution (dashed orange line).

pronounced than the Cameron bands peak. The CO_2^+ ($B^2\Sigma^+ - X^2\Pi$) brightness at the peak is 270 ± 20 kR which gives 3.2 kR when converting to zenith brightness above subsolar point, three times lower than the value (10.9 kR, when converting to subsolar point) predicted by *Fox and Dalgarno* [1981] at F10.7 = 70 and more than twice lower than the value (8.2 kR) predicted by *Gronoff et al.* [2008] at low solar activity (F10.7 = 80). The disagreement should be worse when taking into account the solar activity. It is difficult to explain the difference between the observed brightness ratio CO (a-X) / CO_2^+ (B-X) ~ 7.4 ± 0.7 and the predicted ratio ~2.2 [*Fox and Dalgarno*, 1981] and 2.5 [*Gronoff et al.*, 2008]. *Fox and Dalgarno* [1981] found a CO_2^+ (B-X) brightness of 5.4 kR when assuming a 50% crossover from CO_2^+ B to A electronic state before radiating [*Samson and Gardner*, 1973]. In this case, the ratio of the Cameron bands and CO_2^+ doublet brightness is 3.7 still twice lower than the observed ratio. An exponential fit of the brightness above the peak is indicated on Figure 3. The temperatures deduce from these fits (assuming a scale height dictated by CO_2 gas) are T = 380 ± 40 K and T = 290 ± 60 K for the Cameron and CO_2^+ bands respectively. These derived temperatures are very sensitive to the altitude range chosen for the fit and the error bars include this sensitivity. The temperature derived from the CO_2^+ bands is in agreement with the noon temperature of 259 K at 145 km of the global empirical model of the Venus

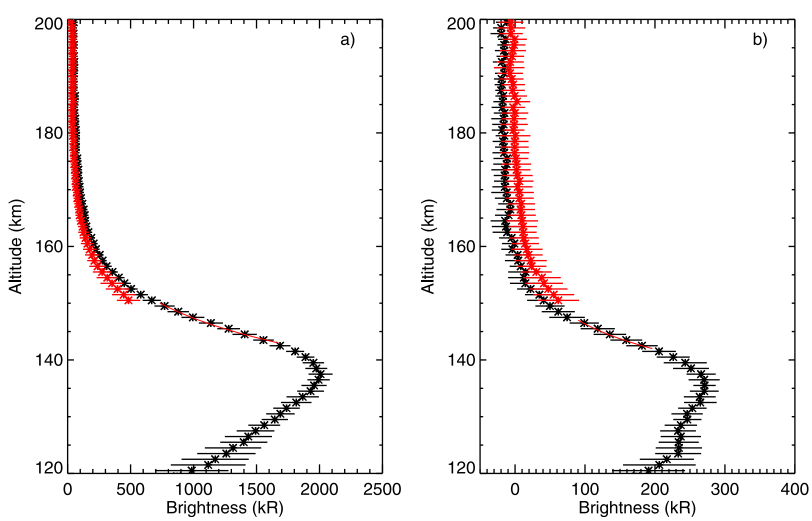

Figure 3. Vertical profile of (a) the Cameron bands and (b) CO_2^+ (B-X) bands brightness obtained from the full set of observations. Measurements from the observations done with alignment mode are indicated by black stars and observations done with the binning mode are indicated by red stars. The observed signal is saturated at all wavelengths with the binning mode preventing to derive the vertical profile below 150 km. The profile above the peak brightness has been fitted by an exponential decrease (red line) to derive the temperature of the upper atmosphere. The altitudes correspond to the altitudes of the tangent point.

thermosphere derived from PVO Neutral Mass Spectrometer measurements [*Hedin et al.*, 1983].

4. Comparison With Mars

[8] The spectral shape of the Cameron bands observed by the same instrument with the same spectral resolution on Mars and Venus is very similar suggesting that similar mechanisms are responsible of these emissions. The brightness of the Cameron bands and CO_2^+ ($B^1\Sigma^+ - X^1\Sigma^+$) doublet at the peak are 2000 ± 100 and 270 ± 20 kR respectively, which is 10 times more than brightness reported on Mars [*Leblanc et al.*, 2006] at solar zenith angles lower than 40°. Venus is closer to the sun than Mars which could explain a factor 4. Therefore, a factor 2.5 between the intensities of Venus and Mars Cameron bands and CO_2^+ still needs to be explained. The main processes of production of CO and CO_2^+ excited states are due to photodissociation, electron impact dissociative excitation and photoionization of CO_2 by UV solar flux [*Fox*, 1992; *Gronoff et al.*, 2008]. The UV solar flux can be estimated at the time of the observations of Mars (October 2004 to March 2005) and Venus (October to December 2011) from the MgII core to line ratio measured by Solstice/Sorce on the Lasp Interactive Solar Irradiance Data Center (LISIRD). This index has been shown to be a good proxy of the EUV variability [*Thuillier and Bruinsma*, 2001]. During Venus observations, the MgII index was ~0.070–0.075 while during Martian observation it was slightly smaller ~0.055–0.065. This difference ~25% is too small to explain the difference observed between the Martian and Venusian brightness dayglow. On Mars a CO(a-X)/CO_2^+ ~5 was derived by *Leblanc et al.* [2006] in good agreement with the ratio of 4.7 found independently by *Cox et al.* [2010] from SPICAM-MEX observations. *Cox et al.* [2010] found that this observed ratio was slightly lower than the modeled ratio ~5.8. These authors also found that a 42% cross over from CO_2^+ B to A electronic state before radiating lead to a good agreement between the observed and modeled CO_2^+ brightness but in this case the modeled CO/CO_2^+ intensity ratio is worse. *Simon et al.* [2009], *Cox et al.* [2010], *Jain and Bhardwaj* [2012] models overestimate the Cameron bands intensity on Mars. This discrepancy was attributed to an overestimate of the electron impact cross section of CO(a-X). The comparison between model and observations of the Cameron bands intensity on Venus supports this conclusion.

[9] As observed on Mars, the temperature derived from the Cameron bands is larger than the temperature derived from the CO_2^+ bands. The ratio between the two temperatures is ~1.3 close to the ratio obtained on Mars. On Mars, the larger scale height of the Cameron bands brightness could result from a production of CO in the $a^3\Pi$ excited state by dissociative recombination of CO_2^+ [*Leblanc et al.*, 2006]. On Venus, *Gronoff et al.* [2008] predict that the CO_2^+ recombination is not an important source to produce CO ($a^3\Pi$), but electron impact on CO is not negligible and becomes the major source above 175 km. A difference between Mars and Venus dayglow emissions, pointed by *Fox* [1992] results from a larger CO mixing ratio in the Venusian upper atmosphere. This larger mixing ratio explains the much larger intensity of the CO ($A^1\Pi - X^1\Sigma$) observed on Venus than Mars by HUT [*Feldman et al.*, 2000]. Solar occultation measurements with SPICAV/SOIR on Venus Express yields at 140 km and terminator a 5% ratio [CO]/[CO_2] [*Vandaele et al.*, 2012] and according to *Hedin et al.* [1983], at 140 km CO represents ~10% of the total density at noon, while on Mars, CO represents less than 1% of the total density at the ionospheric peak [*Nier and McElroy*, 1977]. Underestimate of processes involving CO to the Cameron bands intensity by models could explain the difference observed between Mars and Venus.

5. Conclusion

[10] The spectra of the dayglow emissions obtained by UV channel on SPICAV aboard Venus Express between 110–320 nm are the first observation in the atmosphere of Venus of the CO Cameron bands at 180–260 nm and CO_2^+ doublet at 289 nm. The peak of the CO Cameron bands and CO_2^+ doublet brightness is between 135 and 140 km close to the ionospheric peak with a brightness of 2000 ± 100 and 270 ± 20 kR respectively. The temperature of the upper Venusian atmosphere can be derived from the scale height of the CO_2^+ doublet brightness. A first comparison between the Martian and Venusian emissions show some similarities between their dayglow emissions as expected from a similar composition of the upper atmosphere. The stronger brightness of the Venusian dayglow with respect to Mars dayglow in the 200–300 nm range cannot be explained only by the distance to the Sun and by the difference in EUV solar flux at the time of the observations. Modelling studies are therefore needed to better understand the differences between the Martian and the Venusian dayglow as well as to explain the ratio of the Cameron bands brightness and CO_2^+ doublet brightness. New observations are planned to investigate the variability of the Venusian dayglow with solar zenith angle and solar activity. The spectral resolution of 10 nm of the observations presented in this paper is rather poor and the use of the narrow slit of SPICAV-UV which was not possible until now would be useful to separate the CO_2^+ (B-X) doublet at 289 nm and the oxygen line at 297 nm as observed on Mars. Observations with a higher sensitivity are needed to detect dimmer emissions such as the oxygen line at 130.4 nm not observed here.

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